NAIC-ID(RS)T-0260-95

# NATIONAL AIR INTELLIGENCE CENTER

## DIFFRACTIVE OPTICAL ELEMENTS USED IN INFRARED SYSTEMS

## HUMAN TRANSLATION

NAIC-ID(RS)T-0260-95 3 October 1995

MICROFICHE NR: 95C000617

DIFFRACTIVE OPTICAL ELEMENTS USED IN INFRARED SYSTEMS

English pages: 19

Source: GPS Zai Hang Tian Yao Gan Dui Di Ding Wei
Zhong De 1993, No. 4; pp. 54-58

Country of origin: China
Translated by: SCITRAN
F33657-84-D-0165
Requester: NAIC/TASC/Lt Shaun M. McMahon
Approved for public release: distribution unlimited.

# DIFFRACTIVE OPTICAL ELEMENTS USED IN INFRARED SYSTEMS

**Abstract:** Diffractive optical elements may improve the performance of infrared optical systems. Using standard integrated circuit technology, a method of manufacturing high-quality diffractive optical elements has been researched. Because elements are produced using computers, it is possible to achieve arbitrary phase contours.

**Key words:** holography, holographic optical elements, computer, diffractive optics.

GRAPHICS DISCLAIMER

All figures, graphics, tables, equations, etc. merged into this translation were extracted from the best quality copy available.

# I. INTRODUCTION

Passive and active (laser radar) infrared detection equipment requires very high quality optical systems in order to facilitate achieving the required performance. Within stipulated fields of vision and spectral bands, it is necessary to be able to realize the required characteristics. Optical systems must be composed of multiple single lens elements. When designing optical systems, the three main problems considered are cost, quality, and performance.

Optical systems are normally limited to only including spherical surfaces. Using nonspherical surfaces is capable of reducing the number of elements needed to obtain the required performance. The results of weighing them are that nonspherical manufacture is much more expensive than spherical.

The number of optical materials transmitting infrared wave band is very limited. The majority of infrared lens elements are manufactured from three types of materials using zinc germanicide, silicide, and selenicide. They all exhibit chromatic dispersion. Chromatic dispersion characteristics of these materials lead to optical systems having relatively large numbers of elements. If it were possible to use materials with relatively small chromatic aberrations, lens elements would then be fewer.

---

* Numbers in margins indicate foreign pagination. Commas in numbers indicate decimals.

This article suggests that infrared systems opt for the use of new optical elements having not only refractive properties but also diffractive characteristics. One type of diffractive surface contour corrodes to become the surface of an ordinary spherical lens element. In active systems, the performance of this type of element is similar to nonspherical refraction. Diffractive optical element wave length chromatic dispersion forms an inverse proportion with wave length. However, refractive optical element chromatic aberration forms a direct proportion with wave length. With regard to passive systems, designers strive to take these chromatic dispersion characteristics and put them together in order to facilitate achieving a clean cancellation.

Potential uses of diffractive optical elements have already been known many years [1,2]. In actual systems, the difficulty with applying diffractive optical elements is the lack of a type of industrial art. Using this type of technology, one must be able to design and reliably produce elements whose required high diffractive indices are able to reach the tolerances needed. What Fig.1(a) shows is the case of Fresnel wave band plate phase contours needed to reach 100% efficiencies. $2\pi$ phase depth corresponds to material corrosion depths associated with medium infrared radiation of approximately 2 microns. At the present time, this type of continuous phase contour technology has not yet been produced.

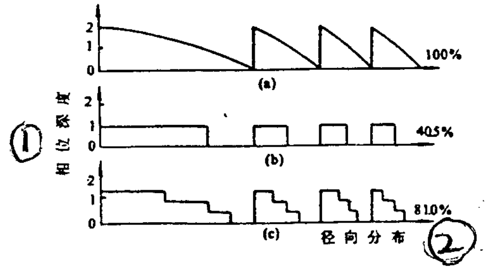


Fig.1 Fresnel Wave Band Plate Phase Contours:

(a) Continuous Contour Having 100% Efficiency, (b) Two Layer Contour Having 40.5% Efficiency, (c) Four Layer Contour Having 81% Efficiency.

Key: (1) Phase Depth (2) Radial Distribution

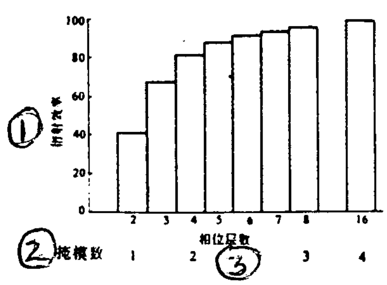


Fig.2 Function Curve Graphs of Two Dimensional Amplitude Masking Templates Required for Multilayer Wave Band Slice Level I Diffraction Indices and Phase Layer Numbers as well as to Produce Phase Layers

Key: (1) Diffraction Index (2) Masking Templates (3) Phase Layer Number

/55

Acting as an approximation method, it is suggested to take continuous phase contours and measure them out to become noncontinuous phase layers [3]. Fig.1(b) and Fig.1(c) represent, respectively, two and four layer quantified Fresnel wave band plate phase contours. The index achieved by this two layer contour is 40.5%, but the index achieved by the four layer contour is 81%. In infrared systems, with regard to these useful elements, diffraction indices reached require having 90% or greater. Fig.2 shows the functional relationships between diffraction indices and the number of phase layers.

One type of method we already designed is capable of accurately and reliably producing multilayer diffraction surfaces with indices of diffraction exceeding 90%. This type of method makes use of technology for circuit manufacture and development (for instance, high resolution photoetching, masking alignment, and active ion corrosion). The second section describes the precise determination of diffraction element optimum design methods used in a given system. The third section describes optimum designs, and, in conjunction with that, methods to accurately manufacture high index multilayer elements with them. The fourth section offers examples of applications to infrared silicon lens technology.

## II. DIFFRACTION ELEMENT DESIGN

The simplest case of high index diffraction optical elements is a Fresnel phase wave band plate [Fig.1(a)]. Collimated monochromatic radiation incident into this structure will be diffracted. Light rays will achieve complete focus. The phase contour needed can be expressed by the use of the simple form below:

$$\Phi(x,y)|_{2\pi} = \frac{2\pi}{\lambda}\sqrt{x^2 + y^2 = f^2} \qquad (1)$$

In the equation, $\lambda$ -- wave length, f -- focal length, $\Phi$ -- estimate modulus $2\pi$.

The Fresnel phase wave band plate is one interesting and limited contour. Normally, one hopes to be able to clearly stipulate any diffraction phase contour.

At the present time, there are large numbers of design programs capable of supplying useful lenses. Among these, most are capable of use in order to describe a universal diffraction phase contour on a given surface. Phase contours are capable in a similar way of describing optical records for holographic optical elements. When the wave lengths and positions are fixed for two coherent point sources in space, the interference diagram synthesized will then describe diffraction phase contours. Using this type of method to describe contour profiles is even more universal than the simple wave band plate. However, this is still one small subset of possible contours. In order to

make phase contour intervals have an even larger possibility of integration, it is possible to take an additional phase term:

$$\Phi(x,y)=\frac{2\pi}{\lambda}\sum_{n,m} a_{nm}x^{n}y^{m} \qquad (2)$$

This is added to the phase determined by the two point sources. With regard to axial phase contours, the two point sources must lie on the light axis. Besides this, if the two point sources are placed infinitely far away, then, their interference effects will be offset. Moreover, phase contours will then be completely described by a general polynomial expansion of equation (2). As a result, one phase contour of a general diffraction phase contour can be placed on any surface of an optical system.

Lens design programs are capable of taking surface curvature, element thickness, and element interval to do variable processing. Moreover, if diffraction phase contours are within systems, then, optimization programs are capable of using polynomial expression coefficients anm to accomplish variable processing. Lens optimization programs will determine the optimum coefficient anm for any specially designated lens system diffraction phase contour.

Information on how to realize high diffraction indices is not included in diffraction phase contours from lens design program specifications and the stipulations of equation (2). Our method requires selecting optimization anm s, after which, a set of two dimensional masking

templates are specified on this basis. The algorithms to design these masking templates are as shown in Table 1. After that, in actual structures associated with high index multilayer diffraction phase contours, use is made of two dimensional amplitude masking templates.

Table 1 Two Dimensional Amplitude Masking Template Algorithms Needed for Construction on the Basis of Given Phase Function Φ(x,y)

Key: (1) Masking Template (2) Filter Section (3) Corrosion Depth (4) Phase Layer (5) Efficiency

| (1) 掩 模 # | (2) 过滤部分 ($l=0,\pm 1,\pm 2,\cdots$) | (3) 腐蚀深度 | (4) 相位层# | (5) 效 率 % |
|---|---|---|---|---|
| 1 | $\Phi(x,y)=(l+1)\pi$ | $\pi$ | 2 | 40.5 |
| 2 | $\Phi(x,y)=\frac{(l+1)\pi}{2}$ | $\pi/2$ | 4 | 81.0 |
| 3 | $\Phi(x,y)=\frac{(l+1)\pi}{4}$ | $\pi/4$ | 8 | 95.0 |
| 4 | $\Phi(x,y)=\frac{(l+1)\pi}{8}$ | $\pi/8$ | 16 | 99.0 |

## III. PRODUCING MULTILAYER CONTOURS

In the past 15 years, the electric circuit industry has established a broad technological foundation for circuit miniaturization. It has developed three key pieces of equipment which are electron beam image generators, active ion corrosion devices, and photoetching devices. E beam image generators are capable of drawing out two dimensional amplitude images possessing 0.1 micron sizes and even higher precision positioning aim. Active ion corrosion devices are capable of taking two dimensional contours and corroding to depths of a few microns. Precisions are a few millimicron. Photoetching devices have already been used to align two images. Precisions are a few fractions of a micron. These are key technological steps forward. The results make it possible to produce high quality diffraction phase contours.

Electron beam image generators produce a two dimensional masking template penetrating through contours. On optical flat plate quartz substrates, a thin layer of chromium uses E beams to produce images. The input to E beam image generators is a document stored on computer magnetic tape. In conjunction with this, it sets up manufacturing forms on specially designated machines. With regard to multilayer diffraction elements, Table 1 sets out algorithms to precisely determine figures which must be drawn. On the basis of these masking templates, the number of phase layers constructed on the final diffraction element is 2n . Here n is the number of masking templates. For example, using only four masking templates will produce 16 phase layers which achieve efficiencies of 99%.

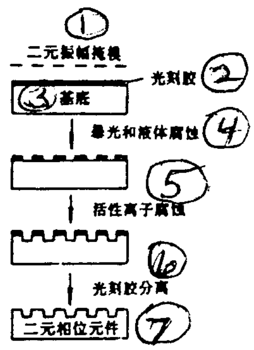


Fig.3 The Process of Two Dimensional Masking Template Producing Phase Contours

Key: (1) Two Dimensional Amplitude Masking Template (2) Photoetching Colloid (3) Substrate (4) Light Exposure and Liquid Corrosion (5) Active Ion Corrosion (6) Photoetching Colloid Separation (7) Two Dimensional Phase Element

After that, two dimensional amplitude masking templates produced by image generators are use in order to construct multilayer optical elements. Manufacturing processes using the first masking template are shown in Fig.3. Optical surfaces which exist on diffraction contours are covered using photoetching gel. After that, masking templates produced by E beams are taken and placed on substrate. In conjunction with this, irradiation is done using standard ultraviolet ray photoetching gel exposure systems. Following that, the photoetching gel is developed, obtaining an appropriate photoetching gel image layer. With regard to active ion corrosion, photoetching gel plays a role in stopping corrosion.

Active ion corrosion is a process in which radio frequency electric fields excite gases producing ions. Ions and substrate materials give rise to reactions. In conjunction with this, use is made of surfaces on which it is possible to control the speed of corrosion. Active ion corrosion processes are anisotropic. As a result, vertical side walls remain which are not continuous phase contours. Classical active ion corrosion speeds are approximately 10~20nm/min. As an example, used on a germanium substrate of 10.6 micron wave length, the first layer corrosion depth which is needed is 1.78 microns. The corrosion time needed is approximately 1.5h. Moreover, it is possible to corrode large numbers of elements at the same time. After the first masking pattern corrodes into the base, it is necessary to eliminate any remaining photoetching gel.

/57

Subsequent to that, the same processes are repeated on optical surfaces. Only this time, using the second masking template, corrosion goes to half the depth of the first iteration of corrosion. With regard to the second and later masking templates, one will have the appearance of even more complexity.

These masking templates must precisely align with the image patterns produced by the first iteration of corrosion. Fortunately, the problem of precisely aligning patterns has already been resolved by the integrated circuit industry. Photoetching machines which can be bought on the market are capable of precisely aligning two pattern forms to within a few fractions of a micron. Speaking in terms of the majority of multilayer structures in visible light and infrared operating ranges, this precision is adequate to maintain diffraction limit properties.

## IV. INFRARED REFRACTION AND DIFFRACTION ELEMENTS

Fresnel wave band plate alignment straight onto monochromatic point light sources is useful. Ordinary nonspherical lenses are capable of playing the same type of role. However, costs are quite high. Using spherical lenses, it is possible to very greatly lower costs. However, it is not possible to reach complete collimation. However, it is possible to make use of spherical lenses, and, in conjunction with that, calculate the needed diffraction contours from lens design programs. When needed diffraction contours are corroded to become spherical lens surfaces, complete collimation will be achieved. The key idea this article puts forward is to let cheap spherical lenses do as much as they can, that is, be able to diffractively calibrate the remaining image aberrations later. Lens elements have both diffractive and refractive characteristics.

Opting for the use of methods combining refraction and diffraction has three main reasons. First, it makes easily

manufactured spherical surfaces take charge of most of the focusing. Tolerances associated with manufacturing and aligning masking templates are capable of decreasing very, very greatly. Second, in optical systems operating within finite fields of vision, in the area of making off-axis aberrations decrease to minimum values, spherical surfaces in themselves are better than flat surfaces. Third, compared to full diffraction elements, system operation wave bands are capable of increasing very, very greatly.

Fully diffractive Fresnel wave band plate focal lengths and wave lengths form inverse ratios. If wave band plates use wave band $\Delta\lambda$ for illumination, it will produce very large longitudinal chromatic variations. The focal points associated with the wave lengths at the two edges of wave bands will be separated by the equation below:

$$\Delta Z = f_C\left(\frac{\Delta\lambda}{\lambda_C}\right) \tag{3}$$

In the equation, fC -- focal length associated with central wave length $\lambda C$ ; $\Delta\lambda/\lambda C$ -- wave band width ratios.

A great many infrared optical system operating wave bands widen to reach 40%. In this type of system, making use of Fresnel wave band plates will make system performance drop.

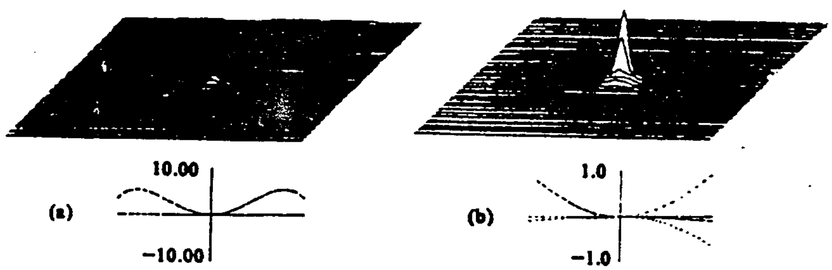


Fig.4 (a) Spherical Silicon Lens Sum (b) Graphic Curves for Nonspherical Silicon Lens Point Spread Function (Top) and Optical Path Differences (Bottom).

Speaking then in terms of wave lengths, using methods very different from wave length plates, combinations of refraction and diffraction are realized. Making lens refractive portions complete most of the focusing, diffractive surfaces only need to calibrate image aberrations. Diffractive surface chromatic aberration influences are very, very greatly reduced. In reality, making use of the remaining chromatic dispersion is beneficial.
*

/58

Silicon is one type of lens material for which chromatic dispersion is not considered great. It is broadly applied in infrared optical systems within the range of 3- 5 micron wave lengths. Single silicon lenses produce chromatic aberrations and spherical aberrations. Normally, the only way to reduce these two types of chromatic aberrations is adding another type of lens to the system. This type of lens is made from different materials possessing different chromatic dispersion properties. It is nothing other than a nonspherical surface made from a germanium-single silicon lens. It is capable of eliminating spherical aberration. However, it still produces chromatic dispersion. On silicon lens surfaces, a multilayer diffractive calibration device is installed. It is capable of very greatly reducing spherical aberration and chromatic aberration.

Fig.4(a) represents an aperture of 50.8mm. Focal length is 101.6mm. Operations are in the point spread function (PSF) associated with spherical surface silicon lenses in wave bands of 3 - 4.5 microns. It also shows the optical path deviation (OPD) for the entire lens aperture. OPD curve diagrams clearly show that lenses not only produce spherical aberration but also

---

* Numbers in margins indicate foreign pagination. Commas in numbers indicate decimals.

produce chromatic aberrations. With regard to surfaces made into the same kind of lenses, the PSF and OPD curves are shown in Fig.4(b). Fig.4(b)'s OPD diagram clearly shows that nonspherical surfaces' calibrations for spherical aberration do not influence chromatic aberration.

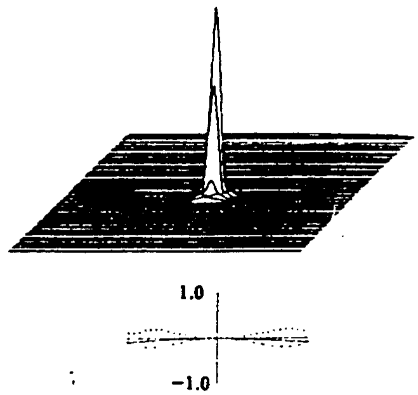


Fig.5 Point Spread Function Associated with Diffractive Calibration Spherical Surface Silicon Lens (Top) and Curve Diagram of Optical Path Deviations (Below)

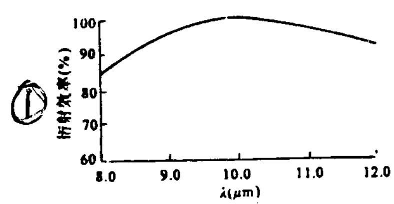


Fig.6 Curve Diagram for Efficiencies from 16 Phase Layer Structures Acting as Wave Length Functions. Design Wave Length is 10 Microns.

Key: (1) Diffraction Efficiency

Fig.5 clearly shows the properties of the same silicon lens. Besides a multiple layer diffractive calibration device placed on the back surface of the lens--PSF and OPD curve graphics clearly show that improvements achieved for diffractive surfaces are increased. Diffractive surfaces calibrate for spherical aberration and chromatic aberration at the same time.

When consideration is given to the use of multilayer diffractive surfaces within finite spectral bands, it needs to be explained that the final problem is how the diffractive indices of these elements change and act as wave length functions. The curve diagrams shown in Fig.6 are composed of diffraction indices associated with 16 layer diffraction surfaces with band widths exceeding 40% (ε-12 microns) and four masking templates. The diffractive efficiency for center wave length locations is 99%. Diffractive efficiencies for the two side wave length locations drop, respectively, to 85% and 90%. Within the entire wave length range, average diffractive efficiencies are approximately equal to 95%. The remaining 5% can make PSF drop 5% (Fig.5). In conjunction with this, it is uniformly distributed on the image surface. In comparison to the curves of Fig.4, in the area of performance, there are still important improvements.

## V. CONCLUSIONS

We developed a type of reliable and accurate method to produce useful diffractive optical elements for use in the middle infrared. All the equipment necessary to manufacture this type of structure has already been developed. In conjunction with this, there are broad uses in the integrated circuit industry.

We raised silicon lens operation in the 3~5 micron wave length range as an example case. This technology is also appropriate to use in germanium lens systems operating in 8~14 micron wave length ranges. (Refer to reference 3. Omitted.)

## DISTRIBUTION LIST

### DISTRIBUTION DIRECT TO RECIPIENT

| ORGANIZATION | MICROFICHE |
|---|---|
| B085 DIA/RTS-2FI | 1 |
| C509 BALLOC509 BALLISTIC RES LAB | 1 |
| C510 R&T LABS/AVEADCOM | 1 |
| C513 ARRADCOM | 1 |
| C535 AVRADCOM/TSARCOM | 1 |
| C539 TRASANA | 1 |
| Q592 FSTC | 4 |
| Q619 MSIC REDSTONE | 1 |
| Q008 NTIC | 1 |
| Q043 AFMIC-IS | 1 |
| E404 AEDC/DOF | 1 |
| E410 AFDTC/IN | 1 |
| E429 SD/IND | 1 |
| P005 DOE/ISA/DDI | 1 |
| 1051 AFIT/LDE | 1 |
| P090 NSA/CDB | 1 |

Microfiche Nbr: FTD95C000617
NAIC-ID(RS)T-0260-95